Evaluation of Performance, Reliability, and Risk for High Peak Power RF Sources from S-band through X-band for Advanced Accelerator Applications

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Burgeoning Worldwide Interest in New Accelerator Based Photon Sources

• Coherent X-ray FELs
  – SLAC LCLS II
  – Los Alamos MaRIE 50 keV (concept)
    • Materials under dynamic loading and irradiation extremes at the microstructure scale
  – Pohang FEL

• Compton gamma-ray sources
  – Lawrence Livermore MEGa-ray at 250 MeV
    • Nuclear material detection
    • Material assay

• Medical imaging, security inspection, and nuclear material detection
Photon Requirements and Facility Definition Driven by Scientific Needs and Applications

• Large parameter space for accelerator design – beam parameters, physical size, efficiency, reliability, etc

• Ultimately choice of RF frequency becomes the key question
  – Availability of RF sources
  – System reliability
  – Cost
  – Available physical space

• S, C, and X-band klystrons are the sources under consideration
S-Band Klystrons Now Define the State of the Art for High Peak Power & Reliability

• SLAC 5045 Klystron
  – > 800 installed on SLAC linac since 1984
  – 2.856 GHz
  – 65 MW peak, 45 kW avg.
  – 350 kV beam voltage
  – 3.5 µs pulse width
  – 180 Hz PRF
  – 8 A/cm² cathode current density
  – 45% efficiency
  – > 80,000 hr MTBF

• 150 MW version built for DESY
Large Number of Tubes (800) and Decades of Hard Operation Have Provided Excellent Statistics

**12 Month Avg MTBF**: total HV hours accumulated on all klystrons during the previous 12 months divided by the total number of failed klystrons during the same period – 80-90,000 hr

**12 Month Age of Failed Klystrons**: total accumulated HV hours for all 5045 klystrons failed during the previous 12 months divided by the number of failed klystrons during the same period – 65-70,000 hr

*Ref. MPOC142 Jensen, et al*
Some 5045s Are Very Long-Lived

- 43 klystrons have exceeded 100K hrs
- 22 are still on-line
- Three > 140K hrs
- Failure modes
  - Cracked/punctured windows
  - End-of-life cathodes
    - Low emission
    - Gun arcing
    - Gas bursts
C-band Klystrons – 66 Toshiba E37202
Klystrons Operating at SPring-8 SACLA*

Toshiba E37202 Ratings

<table>
<thead>
<tr>
<th></th>
<th>Maximum</th>
<th>Typical @ SACLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power</td>
<td>50 MW</td>
<td>30-40 MW</td>
</tr>
<tr>
<td>Beam Voltage</td>
<td>350 kV</td>
<td>300-330 kV</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>2.5 µs</td>
<td>2.5 µs</td>
</tr>
<tr>
<td>PRF</td>
<td>60 pps</td>
<td>10-60 pps</td>
</tr>
<tr>
<td>Efficiency</td>
<td>44%</td>
<td>40%</td>
</tr>
<tr>
<td>Frequency</td>
<td>5.712 GHz</td>
<td>5.712 GHz</td>
</tr>
</tbody>
</table>

* SACLA data provided by T. Inagaki
Run Time Statistics for Toshiba E37202 at Spring-8

- 5 Months of Accelerator Operation from Oct. 2010
- 66 klystrons with 3000-4000 operating hours
- 1 failure at 1200 hours
Several Abnormal Characteristics Observed in E37202 Performance

- 30 out of 70 klystrons exhibit > 10 GHz oscillation late in the HV pulse, with NO RF drive
- Couples to input and output
- No oscillation > 230 kV
- Not an operational issue

- 4 klystrons out of 70 have discontinuities in the $P_{\text{drive}}$-$P_{\text{output}}$ power curve
- Output is unstable at <100 W drive
- Multipactor suspected
- Non-issue-normal operation > 200 W drive
X-Band Klystrons –SLAC XL4 & XL5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power</td>
<td>50 MW</td>
</tr>
<tr>
<td>Beam Voltage</td>
<td>440 kV</td>
</tr>
<tr>
<td>Beam Current</td>
<td>350 A</td>
</tr>
<tr>
<td>RF Pulse Width</td>
<td>1.5 μs</td>
</tr>
<tr>
<td>PRF</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Freq. XL4/XL5</td>
<td>11.424/12.0 GHz</td>
</tr>
<tr>
<td>Perveance</td>
<td>1.2 μP</td>
</tr>
<tr>
<td>Efficiency</td>
<td>~ 40%</td>
</tr>
<tr>
<td>Focusing solenoid</td>
<td>4.6 kG/23 kW</td>
</tr>
</tbody>
</table>
X-band Development Program Produced 3 Distinct Series of Klystrons: XC, XL, PPM

### X-band Klystron Design and Performance Specifications

<table>
<thead>
<tr>
<th>Tube Name</th>
<th>Solenoid Focused</th>
<th>PPM Focused (6 Tubes)</th>
<th>Solenoid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XC (8 Tubes)</td>
<td>XL-PPM</td>
<td>XL5 (5 Tubes)</td>
</tr>
<tr>
<td></td>
<td>XL1-XL4 (26 Tubes)</td>
<td>75 XP-1</td>
<td>75 XP-3</td>
</tr>
<tr>
<td>Peak Pwr (MW)</td>
<td>100</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>RF Pulse Length</td>
<td>1 µs</td>
<td>1.5 µs</td>
<td>1.5-2.4µs</td>
</tr>
<tr>
<td>Beam Voltage (kV)</td>
<td>440</td>
<td>440</td>
<td>490</td>
</tr>
<tr>
<td>Beam Current (A)</td>
<td>520</td>
<td>350</td>
<td>190</td>
</tr>
<tr>
<td>µP</td>
<td>1.8</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Achieved</td>
<td>51 MW @ 1 µs &amp; 60 Hz</td>
<td>50 MW @ 1.5 µs &amp; 60 Hz</td>
<td>50 MW @ 1.5-2.4 µs</td>
</tr>
<tr>
<td>Notes</td>
<td>Low efficiency</td>
<td>In production</td>
<td>Gain instability</td>
</tr>
</tbody>
</table>

Notes: Low efficiency, Gain instability, Spurious oscillation, Excessive interception, Air cooling limited $P_{avg}$, In production.
More than 30 XL4 & XL5 Klystrons Have Been Built

- XL4s routinely power test stands for high gradient experiments and testing RF structures
- Several have logged >10,000 hours but mostly below 35 MW
- One XL4 powers the LCLS phase space linearizer – has run 25,000 hr at 20-25 MW at 60 and 120 Hz
- LCLS X-band deflection cavity will also require an XL4
- Preparing to conduct a life test on a new XL4
- During testing at full spec 50 MW, 1.5 µs, 60 Hz, no breakdowns observed during 24 hr heat run
XL Klystron Is a Solid Design with a Growing Track Record

- Small number of tubes (~30) and widely variable operating conditions => insufficient run time statistics for a meaningful MTBF calculation
- With increased operating experience and incremental improvements will likely become more widely use in accelerator applications
- Effort underway to transfer design of the XL5 to industry for production
# Klystron Reliability Summary

<table>
<thead>
<tr>
<th></th>
<th>S-Band SLAC 5045</th>
<th>C-Band Toshiba E37202</th>
<th>X-Band SLAC XL4/5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power max</td>
<td>65 MW</td>
<td>50 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td># of tubes</td>
<td>&gt; 800</td>
<td>68</td>
<td>30</td>
</tr>
<tr>
<td>Operating Hours</td>
<td>&gt; 25 x10^6</td>
<td>284,000</td>
<td>&lt; 100,000 (estimated)</td>
</tr>
<tr>
<td>Reliability</td>
<td>&gt; 80,000 hr Average MTBF over 3 yrs</td>
<td>Insufficient operating experience for MTBF, but infant mortality is low.</td>
<td>Insufficient operating experience for MTBF calculation</td>
</tr>
</tbody>
</table>
Conclusions

• S-band klystrons have a well established track record for high reliability in hard operation

• C-band klystrons have only recently been chosen for large accelerators
  – Maturity is low
  – Infant mortality is low with operation at 60-80% of max power level

• X-band klystrons
  – Extensive R&D history but operational maturity is low
  – Solid design with growing track record
  – Incorporated into operational facilities
  – Design being transferred to industry